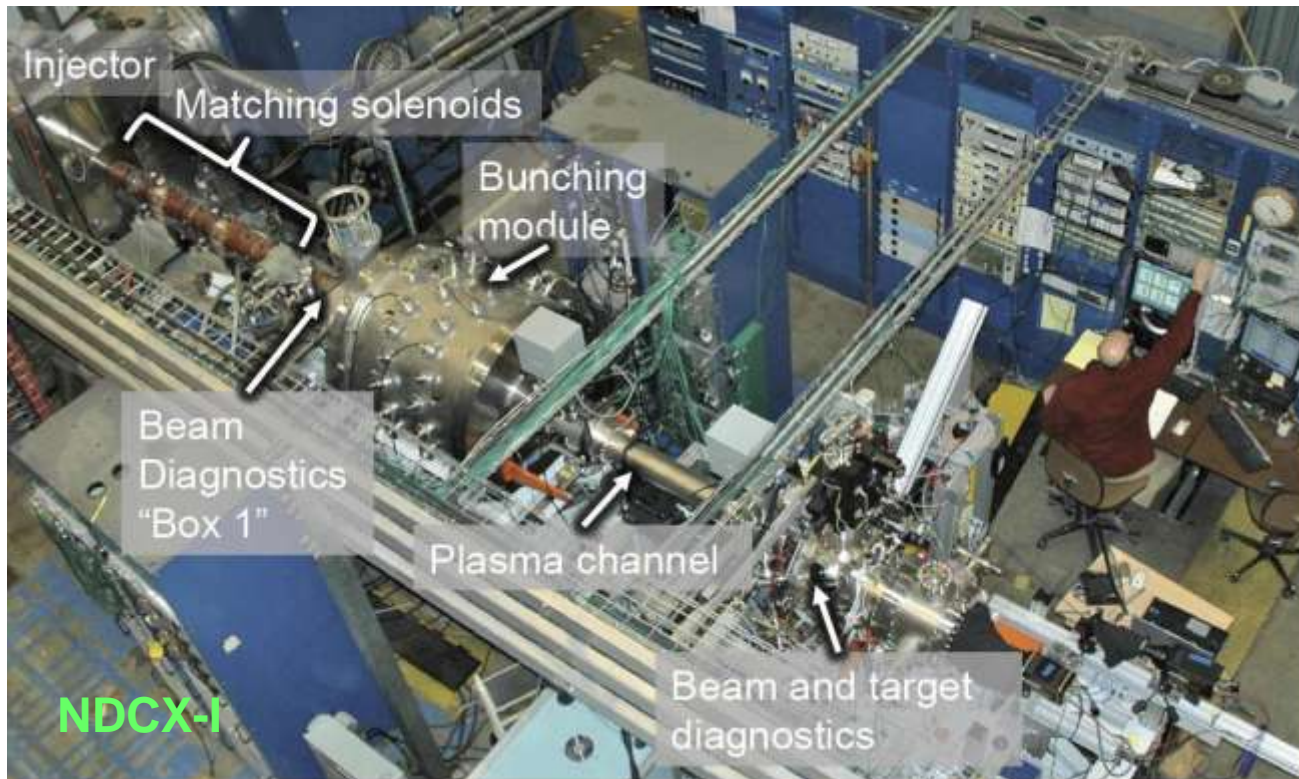


# Ion beam driven HEDP experiments at HIFS-VNL

F. M. Bieniosek, J.J. Barnard, E. Henestroza, J.Y. Jung, S. Lidia, R.M. More, P.A. Ni, P.K. Roy, P.A. Seidl, and W.L. Waldron  
HIFS-VNL (LBNL, LLNL, PPPL)



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Symposium on Heavy  
Ion Inertial Fusion  
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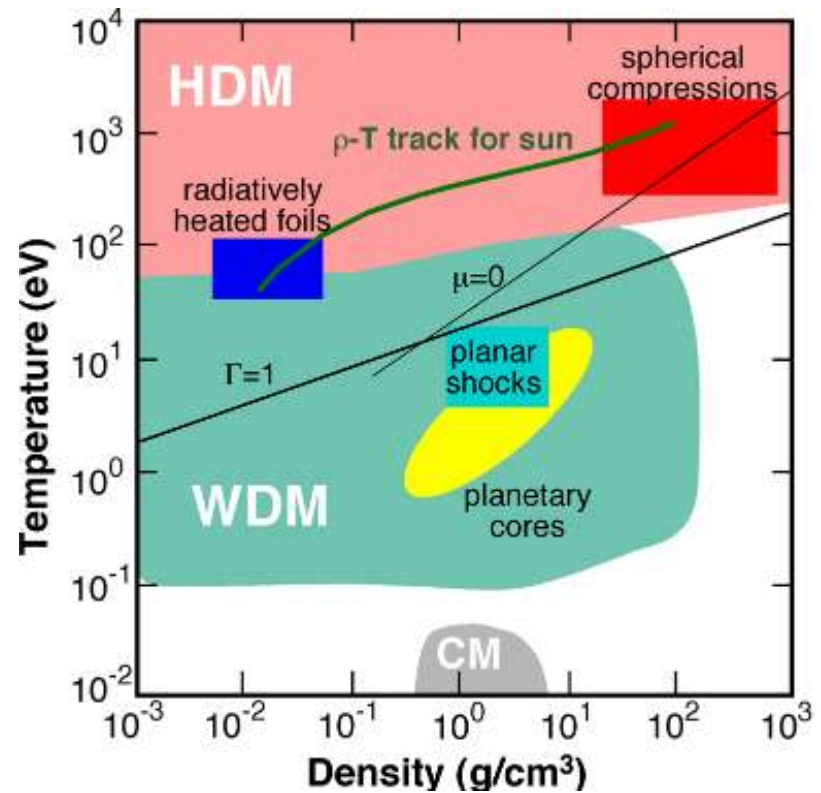
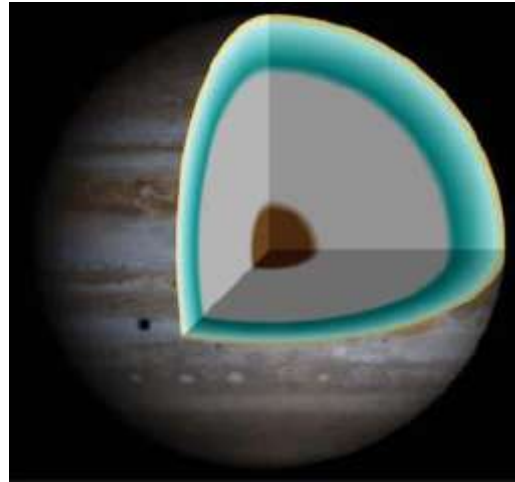
**The Heavy Ion Fusion Science Virtual National Laboratory**



# Overview of HIFS-VNL target experiment program

- HIFS-VNL is a heavy ion fusion science program but main experimental effort is in the area of ion beam driven high energy density physics (HEDP).
- We have recently held a workshop on ion beam driven HEDP.  
-2010 Ion Beam Driven High Energy Density Workshop, June 22-24, 2010  
<http://hifweb.lbl.gov/public/BeamHEDP2010/Presentations.html>
- NDCX-I (0.3-MeV  $K^+$ ) is a test bed for beam manipulation, target physics and diagnostic development.
- NDCX-II (2-3 MeV  $Li^+$ ) is a linear induction accelerator, under construction. It will be an ion beam driven user facility, to be available for target experiments after beam commissioning, in 2012.
- New target chamber with enhanced capability for diagnostics to be designed for installation on NDCX-II; e.g. high power lasers, cryo-targets, x-ray diagnostics.
- This presentation focuses on target chamber HEDP experiments in NDCX-I and NDCX-II.

Understanding the nature of high energy density matter enhances our understanding of the universe and enables important applications.



Astrophysics

Planetary physics

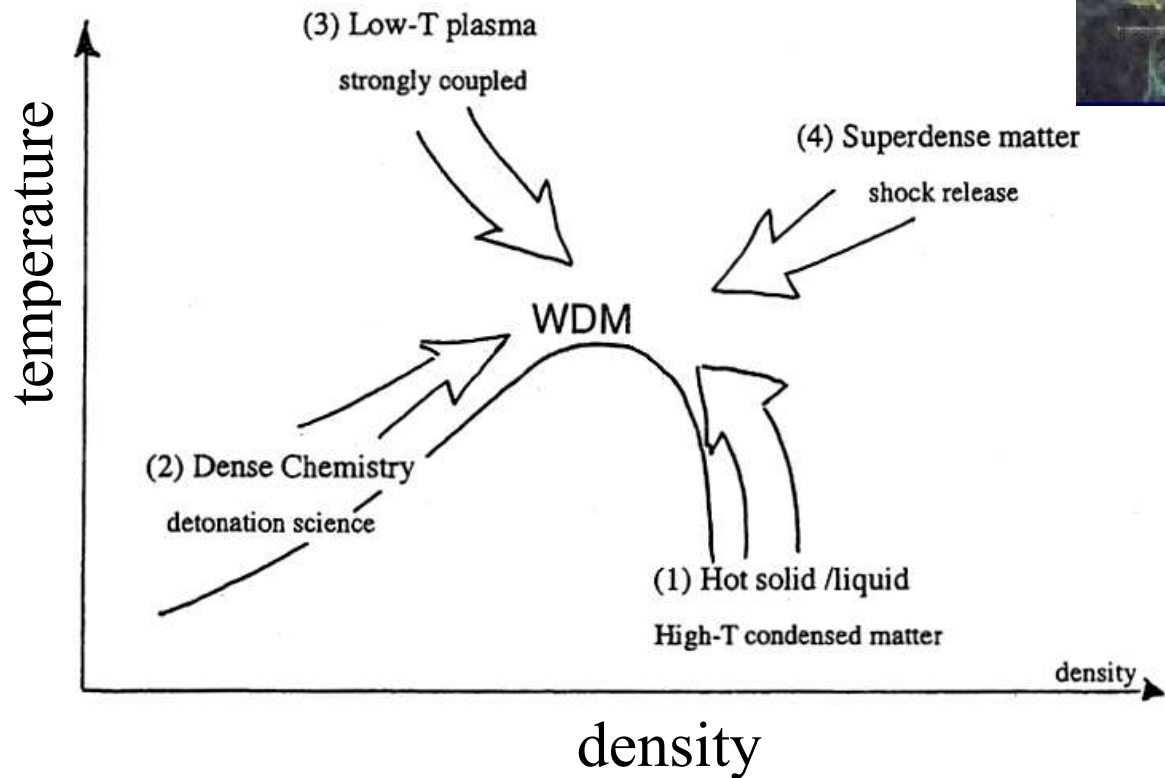
Inertial fusion

Material science & engineering



# Warm dense matter is at the meeting point of several distinct physical regimes - a scientifically rich area of High Energy Density Physics.

From R. More, Warm Dense Matter School, LBNL,  
Jan. 10-16, 2008. <http://hifweb.lbl.gov/wdmschool/>



Many properties in this regime are not well known.



## Unknown properties:

EOS ( $p(\rho, T)$ ,  $E(\rho, T)$ )

Liquid-vapor boundary

Latent heat of evaporation

Evaporation rate

Surface tension

Work function

Electrical conductivity

$dE/dX$  for hot targets

## Phenomena:

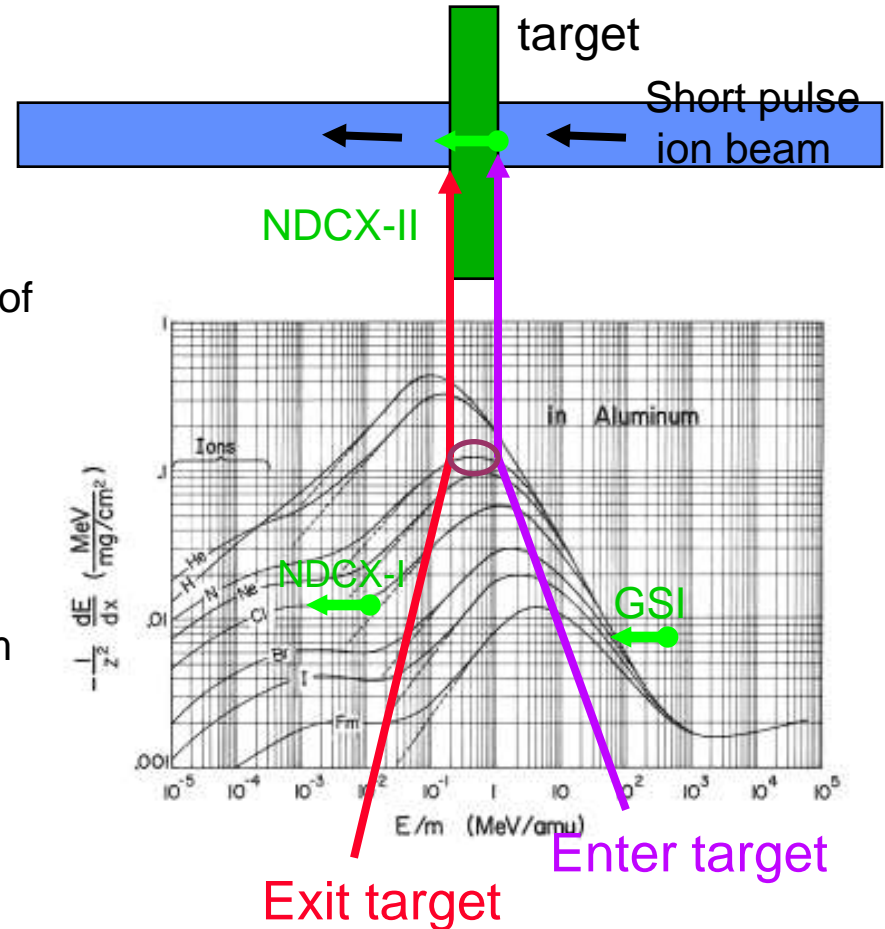
Metal-insulator transition

Phase transitions?

Plasma composition?

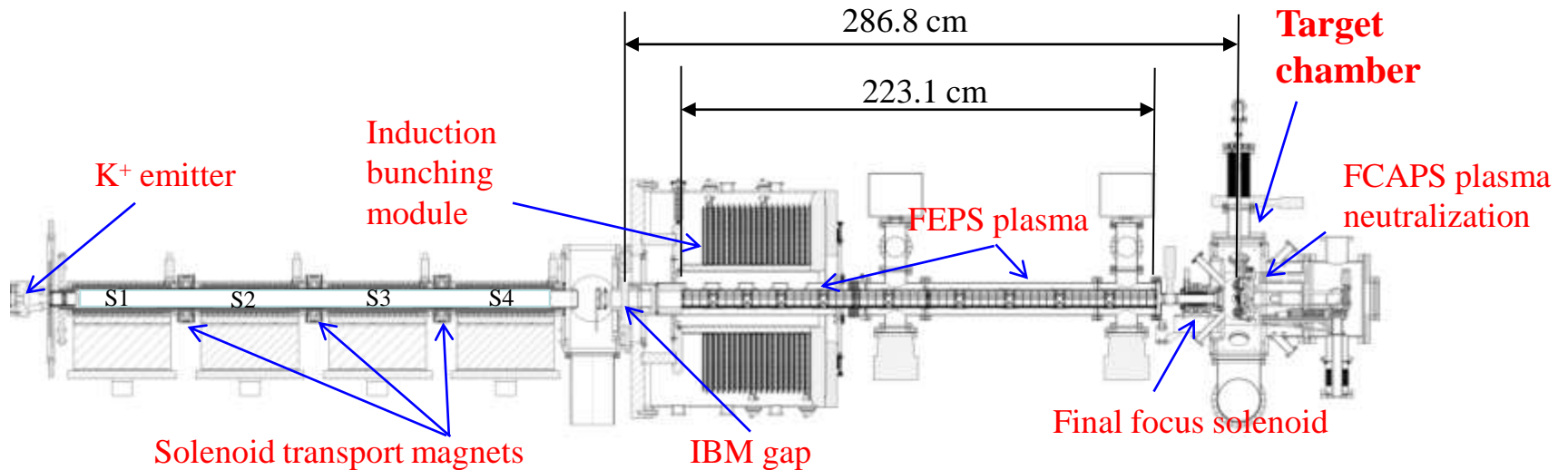
# Ion beams provide a tool for generating homogeneous warm dense matter.

- Warm dense matter (WDM)
  - $T \sim 0.1$  to  $10$  eV
  - $\rho \sim 0.01 - 1 \times \text{solid density}$
- Uniform energy deposition near flat portion of  $dE/dx$  curve, e.g. nuclear stopping plateau (NDCX-I); Bragg peak (NDCX-II)
- Other favorable characteristics include
  - Precise control of energy deposition
  - Large sample size  $\sim$ micron depth,  $1$  mm diameter  $\rightarrow$  easy to diagnose
  - Ability to heat any target material  $\rightarrow$  broad industrial applications
  - Not sensitive to 'bleaching'
  - Benign environment for diagnostics
  - Immune to blowoff plasma
  - High rep rate and reproducibility



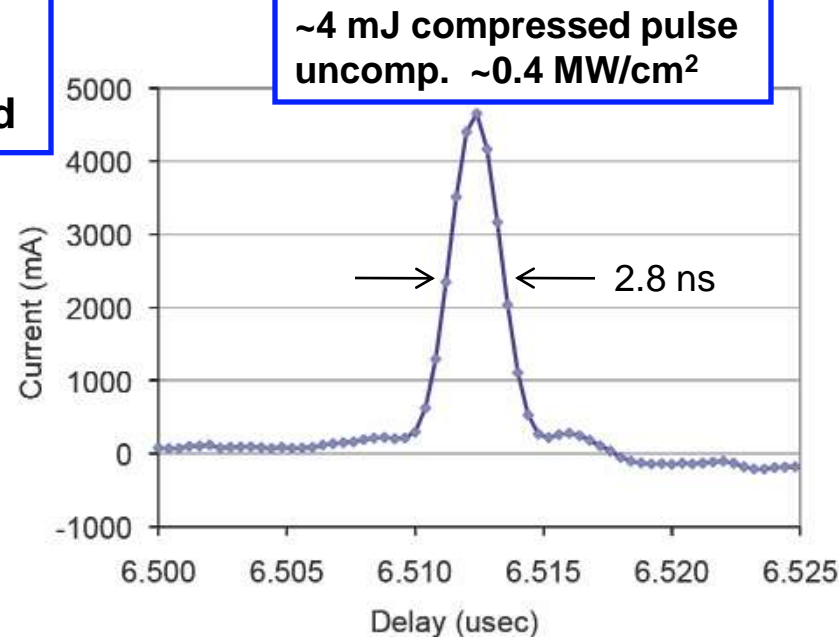
L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970)

Neutralized Drift Compression Experiment - I (NDCX-I) compresses beam  $\sim 100\times$ , using inductive bunching and plasma-based space charge neutralization.



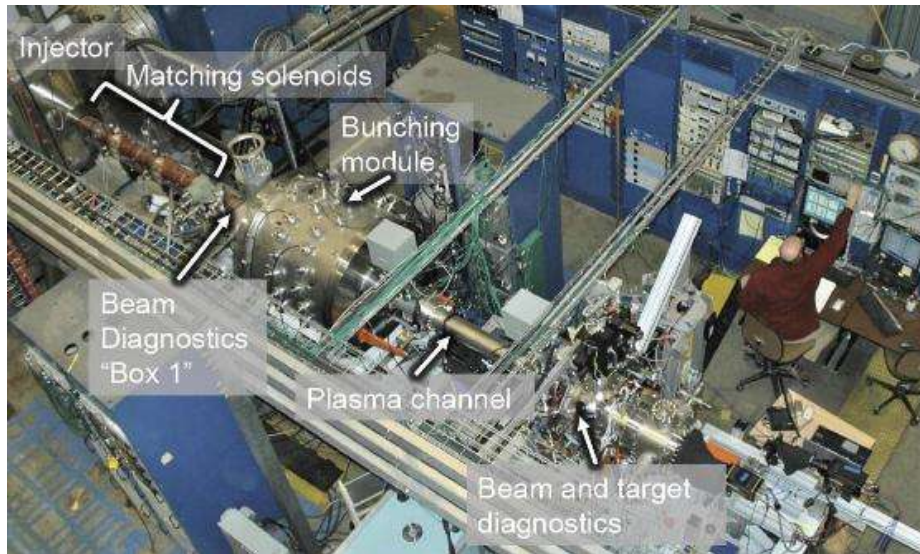
**Velocity tilt  
accelerates tail,  
decelerates head**

**Neutralizing  
plasma is  
required for final  
focus**



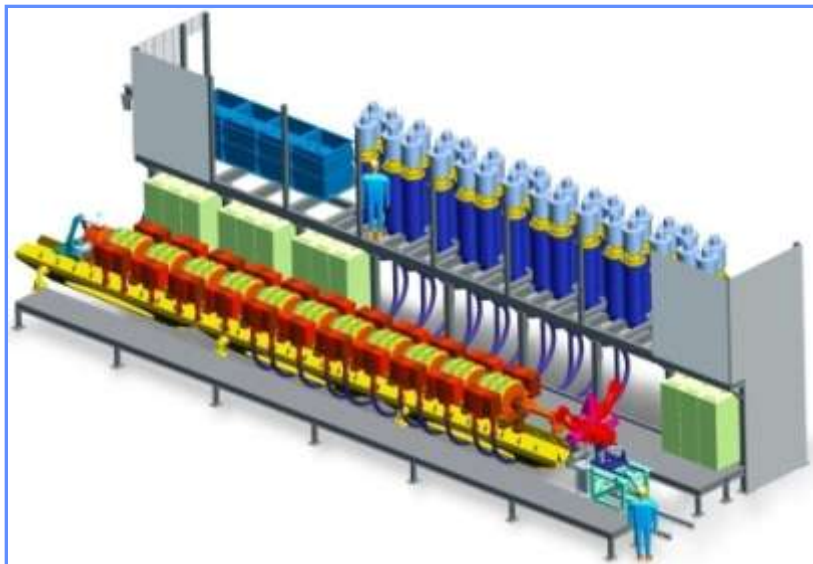
# NDCX I is laying the groundwork for NDCX II.

→  
**NDCX I**  
**0.3 MeV,**  
**0.01  $\mu\text{C}$**   
**2 ns**  
**Now**



- Explore liquid/vapor boundaries at  $T \sim 0.4 \text{ eV}$
- Evaporation rates and droplet formation
- Test beam compression physics
- Develop diagnostics

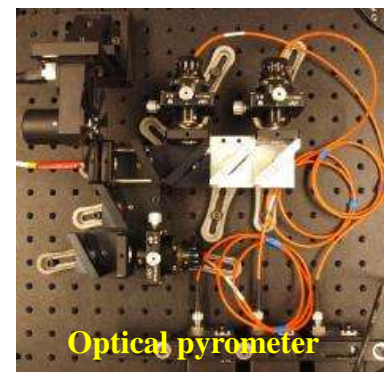
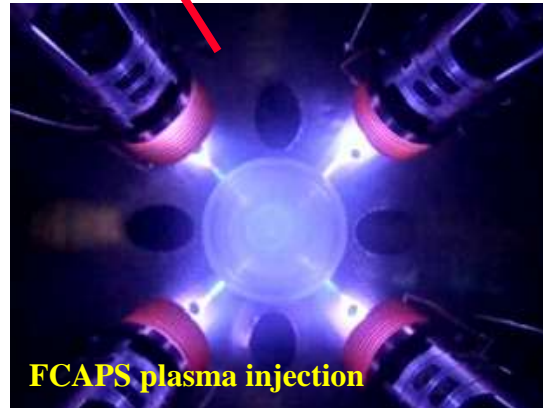
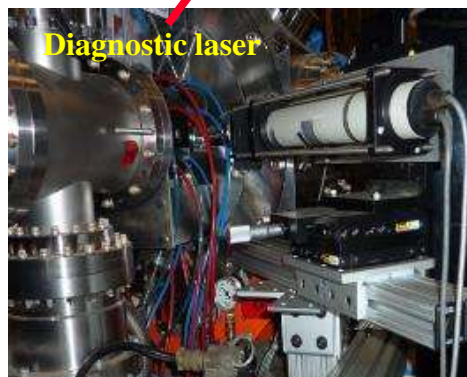
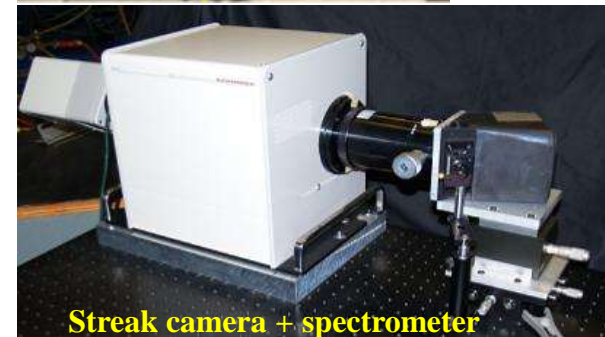
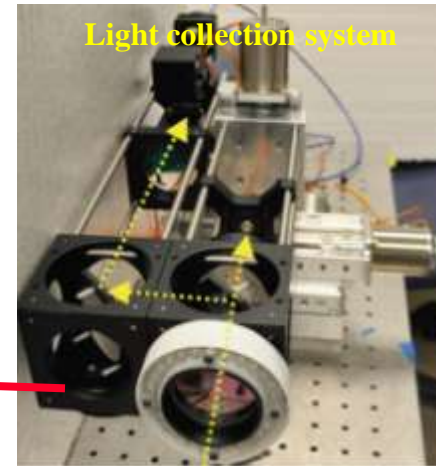
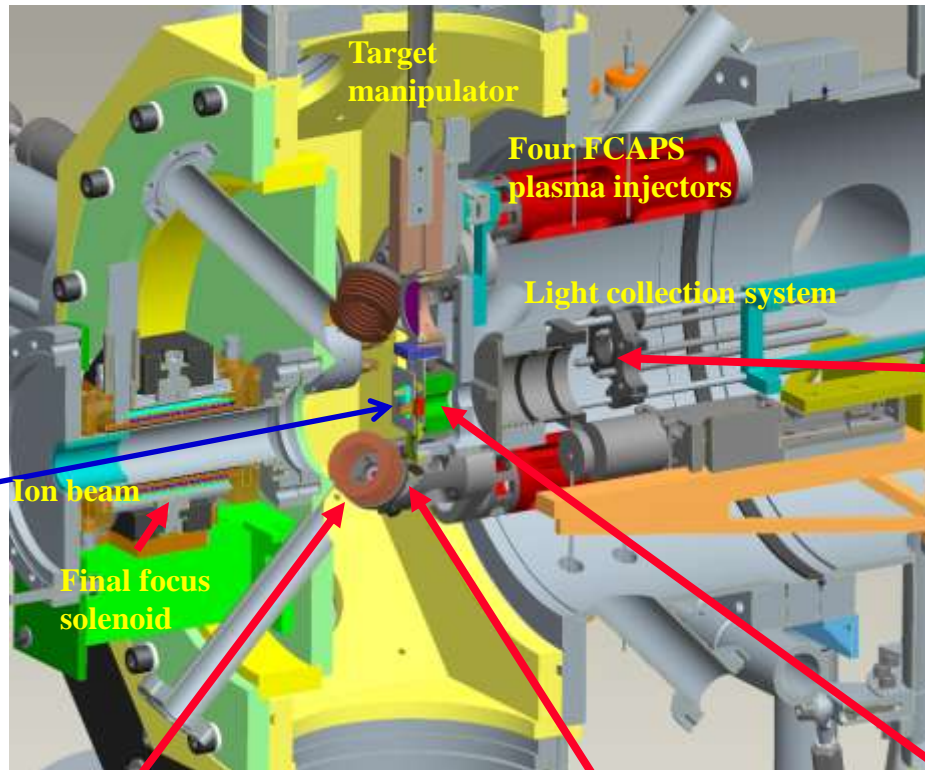
→  
**NDCX II**  
**2 - 3 MeV,**  
**0.03  $\mu\text{C}$**   
**<1 ns**  
**Completion**  
**date: 2012**



- Bragg peak heating
- $T \sim 1\text{-}2 \text{ eV}$  in planar targets
- $\text{Ion}^+/\text{Ion}^-$  plasmas
- Critical point; complete liquid/vapor boundary
- Transport physics
- HIF coupling and beam physics



# NDCX-I target chamber contains target, neutralizing plasma, and target diagnostics.





# NDCX-I provides a test bed for target physics studies, target diagnostics development, and ion beam compression studies.

Target diagnostics include

- Thermal emission
- High speed optical pyrometer
- High speed I-CCD cameras
- Streak camera
- Optical spectrometer
- Laser transmission
- Beam transmission
- Beam scattering (scintillator)
- Calorimeter foil target
- VISAR
- Laser reflection/polarimetry

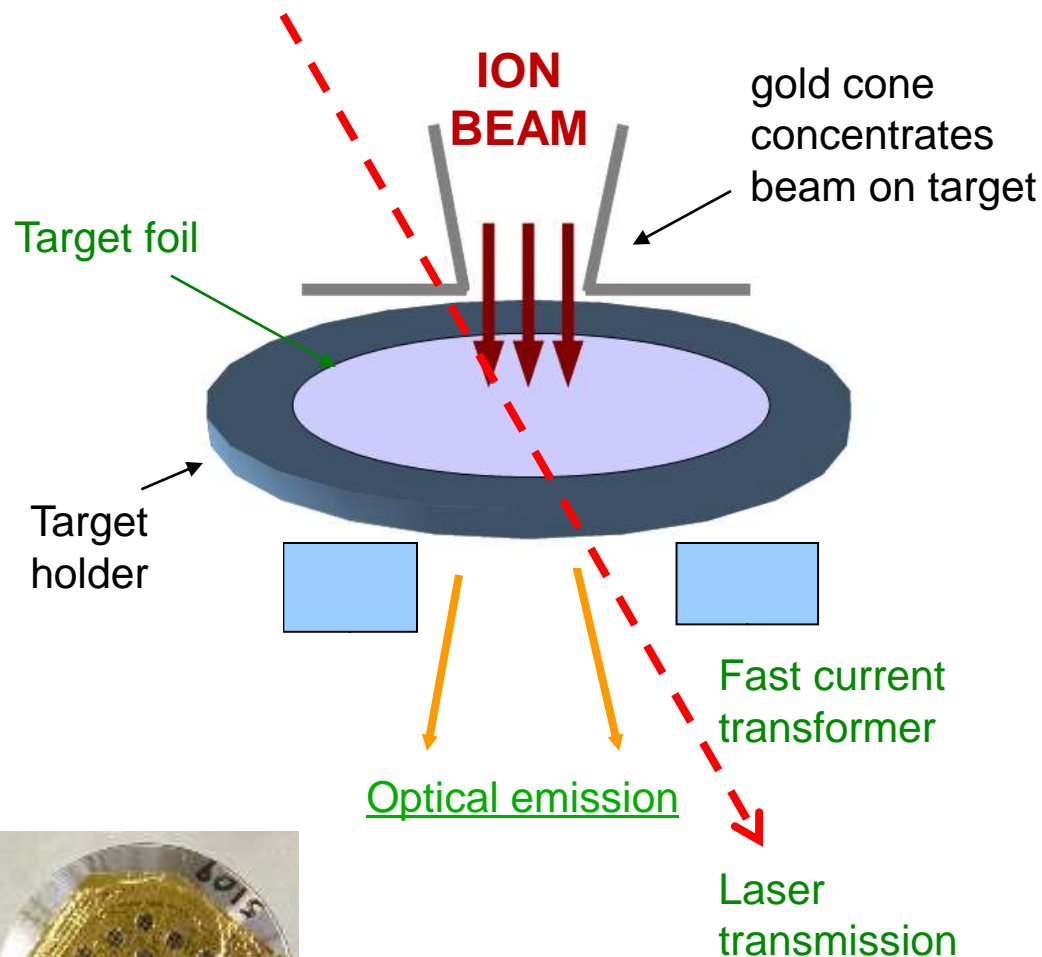
Various targets (>500 shots) :

**Au (0.06, 0.15, 0.5  $\mu\text{m}$ )**

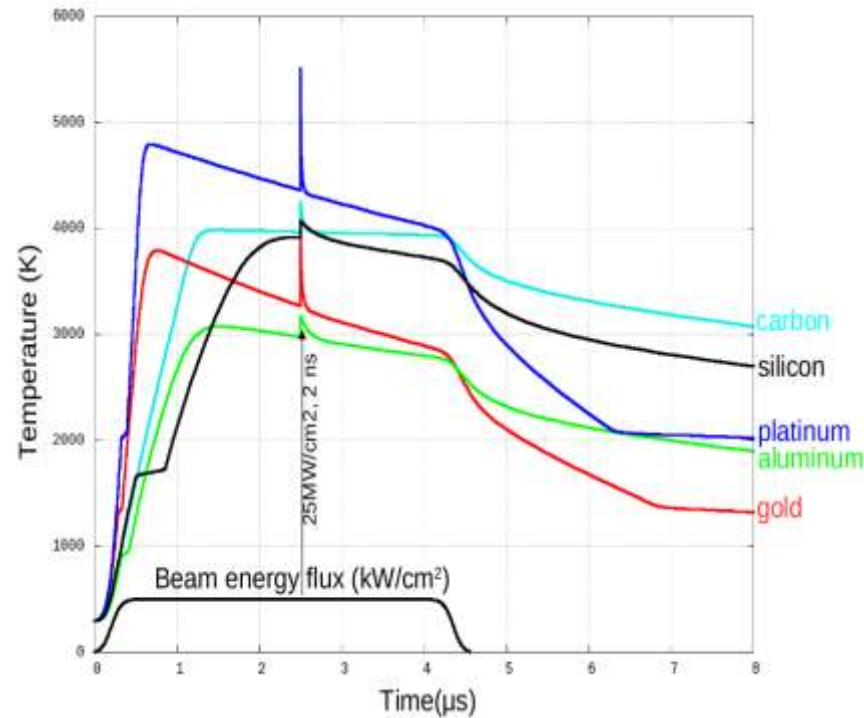
**Pt (0.12  $\mu\text{m}$ ), W (3  $\mu\text{m}$ )**

Al, C, Si (0.4  $\mu\text{m}$ )

Nb (0.2  $\mu\text{m}$ )

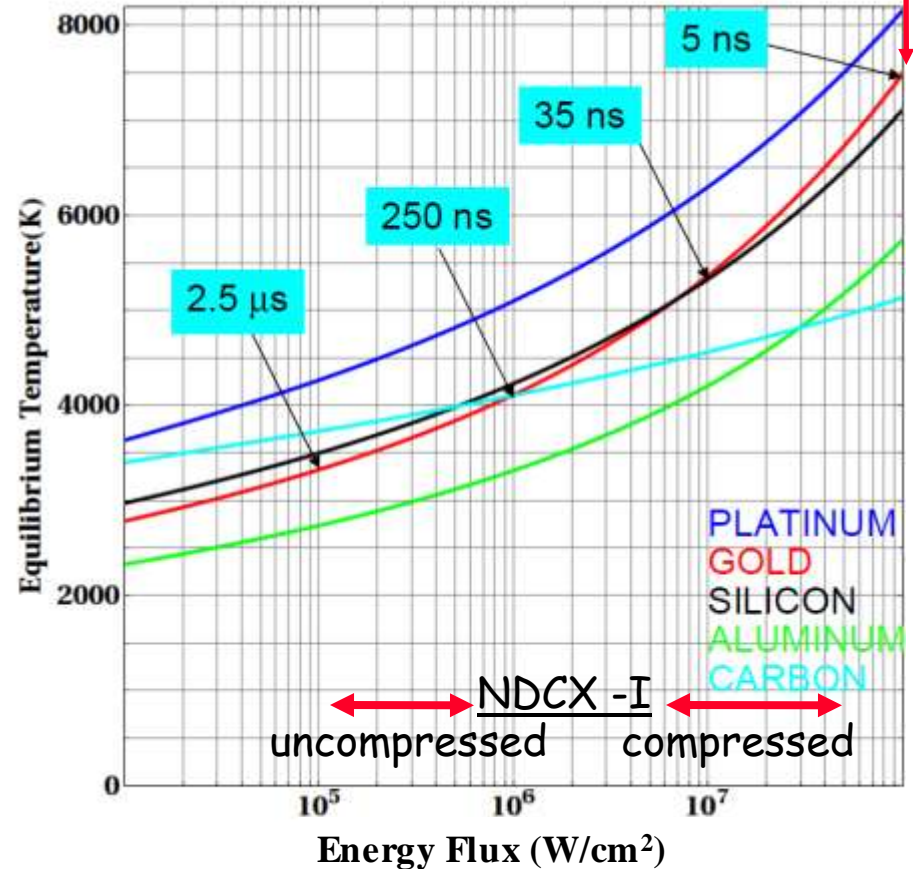


Target heating models predict  $T \sim 0.3 - 0.5$  eV using NDCX-I beam;  $T \sim 1 - 3$  eV using NDCX-II beam.



Times indicate time required to reach equilibrium.

Critical point of gold



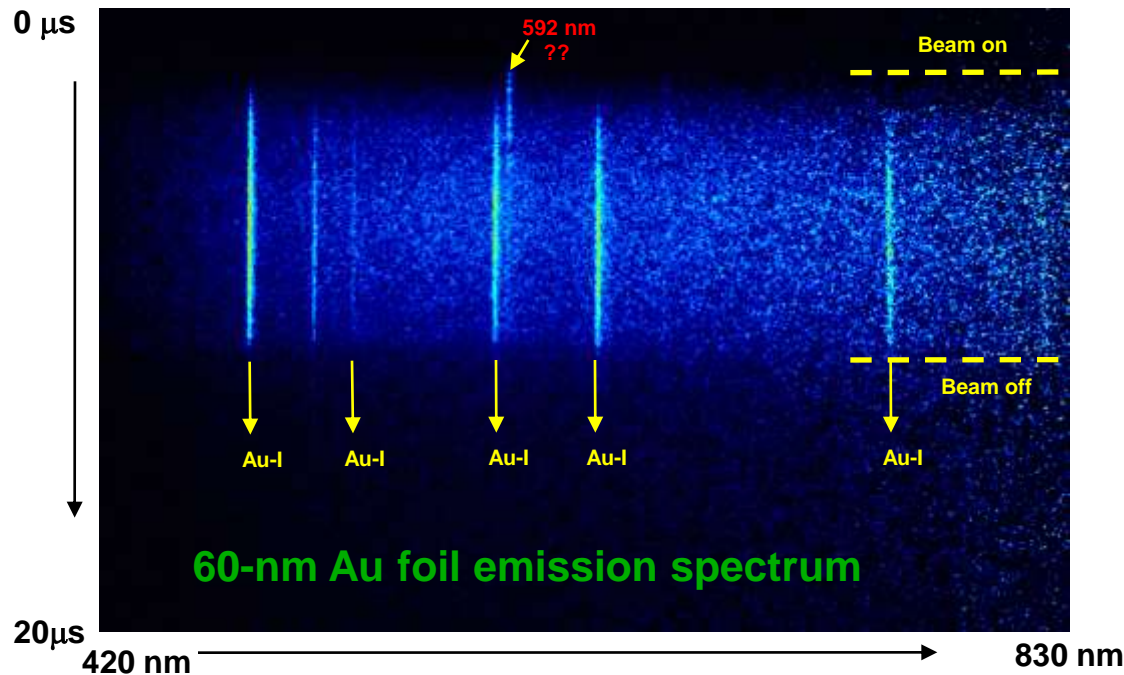
NDCX-II: power/unit area increased >100x

## Recent experiments on NDCX-I.

- Fast optical pyrometry of targets
- Response of target to compressed pulse
- Ion beam transmission and scattering in heated foils
- Final focus cone studies – measure increase of beam intensity on target using cone
- Ion beam manipulation and compression studies
- Droplet formation on  $\mu\text{s}$  time scale
- Stability of thick ( $>$  range) vs. thin ( $<$  range) Au targets
- 3 micron tungsten foil: solid-liquid transition and calorimeter
- Laser transmission in heated foils
- IR thermal emission in heated foils: comparison of response of Au, Pt, Nb
- Spectroscopic studies
- Polarization of optical emission

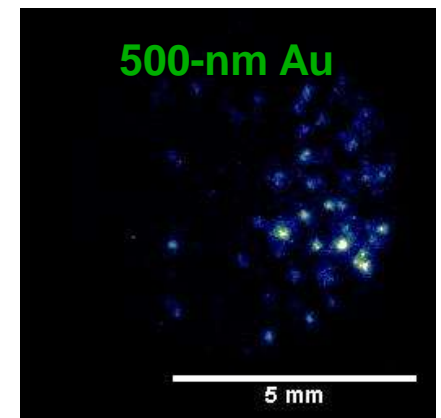
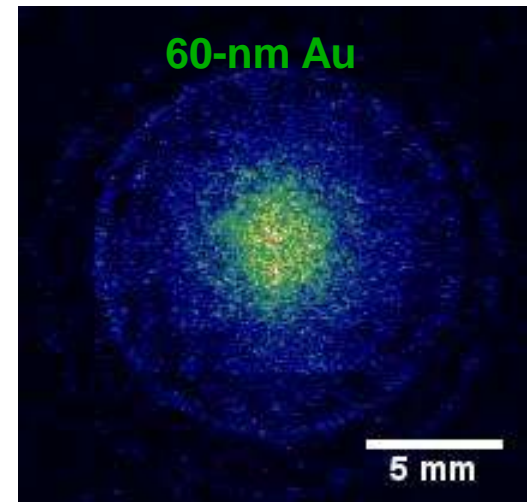


We are studying target behavior with optical and beam-based diagnostics.



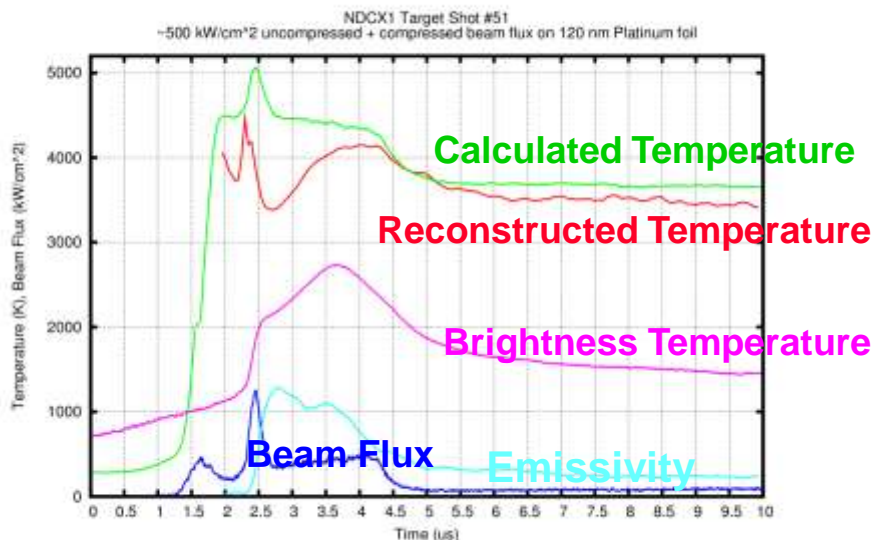
Streak-spectrometer data shows continuum radiation from liquid droplets and beam-pumped Au I lines indicating beam transport through the droplets and the cloud of Au vapor.

Images of target at  $t = 500 \mu$ s show target debris.

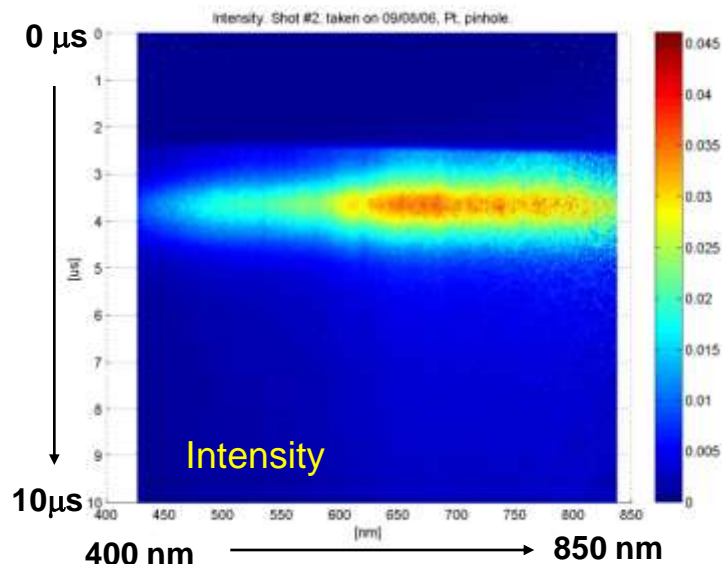
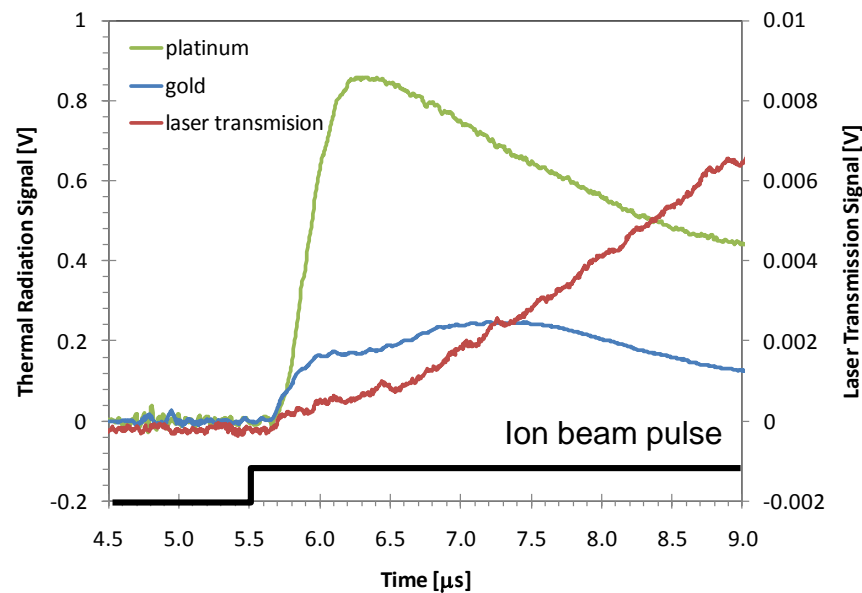


Pyrometer measures target  $T \leq 4500$  K. Thermal radiation, laser, ion beam transmission show droplet formation in  $t < 1 \mu\text{s}$ .

### Streak-spectrometer pyrometer data



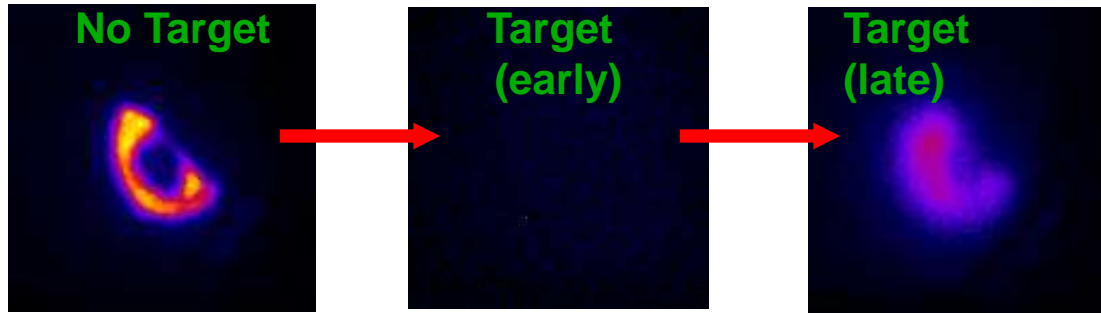
### IR thermal radiation and laser transmission data



-Peak in thermal radiation and laser transmission data indicate target is breaking up on  $\mu\text{s}$  time scale.

-Melting shelf (Au) is a measure of beam intensity and calibration of thermal diagnostics. (See talk by P. Ni).

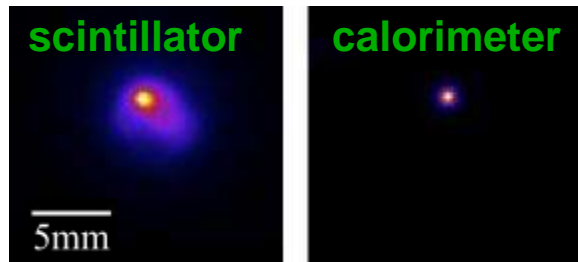
# Beam scattering /stopping follows evolution of target; tungsten foil calorimeter calibrates beam intensity.



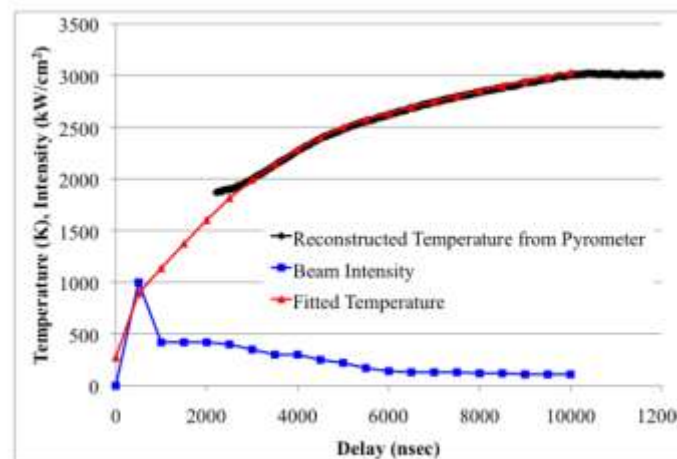
Images of beam scattering on scintillator downstream of target target foil indicate evolution of target during experiment.

Target intact,  
no beam  
transmission.

Beam is transmitted  
and scatters on  
vapor cloud.



Comparison between  
scintillator and tungsten foil  
calorimeter images of  
beam at final focus.



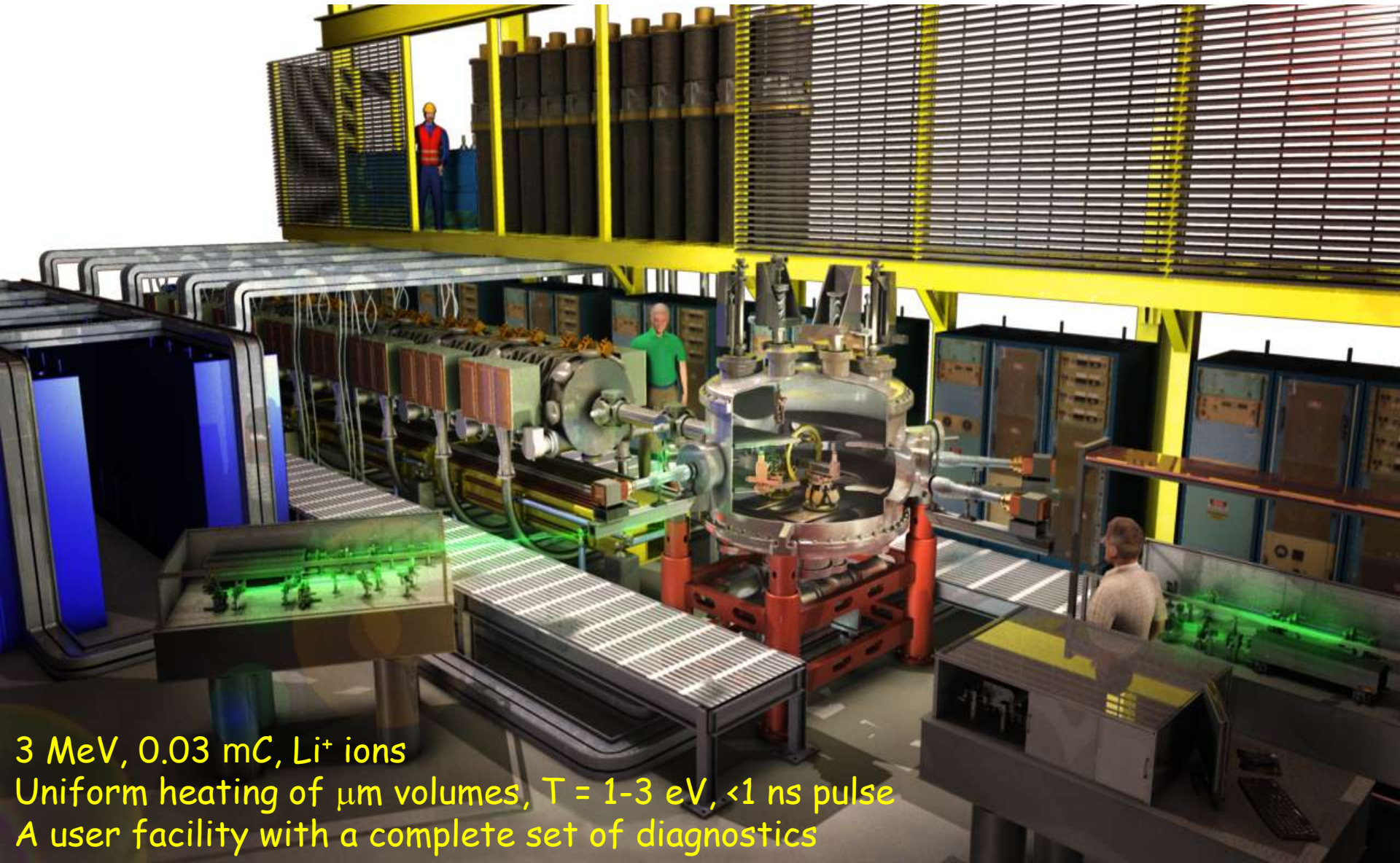
Tungsten foil calorimeter  
provides beam intensity  
information based on  
temperature from  
pyrometer. (See poster by  
S. Lidia).



# Experiments to be done on NDCX-I (and continue on NDCX-II):

- Diagnostic development
  - Polarimetry of target thermal emission
  - Aerogel fragment catcher
  - VISAR (target expansion velocity)
  - Gas jet for spectroscopic beam profile measurement
- Physics of ion beam compression and space-charge neutralized final focus
- Response of target to optimized compressed pulse
- Droplet formation on  $\mu\text{s}$  time scale in liquid metals
- Stability of thick ( $>$  range) vs. thin ( $<$  range) Au targets
- Funnel cone optimization
- Transient darkening, changes in optical properties (metal-insulator, other phase transitions)
- Aerogel target: effect of porous materials, transient darkening
- Fragmentation/fracture mechanics of materials under extreme conditions (e.g. carbon, silicon)
- Beam scattering, charge state,  $dE/dx$  in WDM targets
- Target electrical conductivity, evaporation rate, ...

# NDCX-II Warm Dense Matter Research Facility is under construction (completion 2012).



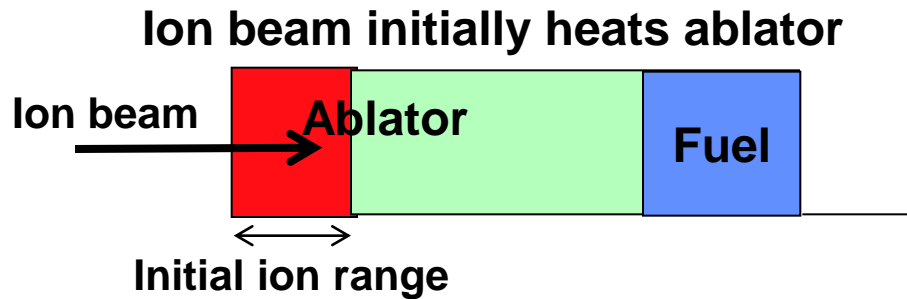
3 MeV, 0.03 mC,  $\text{Li}^+$  ions  
Uniform heating of  $\mu\text{m}$  volumes,  $T = 1\text{-}3\text{ eV}$ ,  $<1\text{ ns}$  pulse  
A user facility with a complete set of diagnostics

# NDCX-II will provide an exciting facility for beam-driven high energy density and IFE target physics

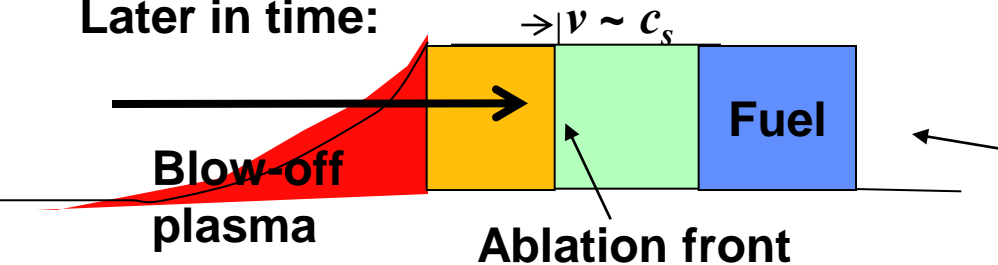
- Increased beam intensity  $>100\times$  ( $\sim 10^{10}$  W/cm<sup>2</sup>) at final focus, shortened pulse (sub-ns) and longer ion range ( $\sim 10\times$ ) in NDCX-II will greatly increase experimental capabilities to study WDM ( $\sim 7\text{-}10$  kJ/g in Al). Possible experiments include:
  - Continue experiments from NDCX-I
  - Phase transitions, esp. liquid-gas interface, critical point
  - Porous targets
  - Positive/negative ion targets
  - Mapping critical density surface using multi-wavelength optical probe
  - Shock wave and other studies related to IFE
  - Shock physics related to WDM
  - Ion beam dynamics (focusing, neutralization -- see talk by A. Friedman)
  - Cylindrical/spherical bubble implosions
  - Possible final focus upgrades
    - High field final focus solenoid
    - Plasma lens



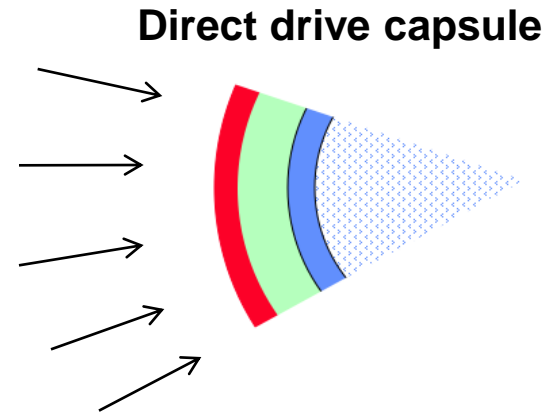
# Direct-drive coupling experiment can be performed on NDCX-II by ramping beam energy.



**Later in time:**



Ramp beam energy to position peak energy deposition to follow shock front  
=> Potentially high coupling efficiency.



Perform experiment by placing target upstream of longitudinal focus to optimize energy ramp.

- Diagnostics include VISAR to measure shock strength at downstream surface of the target
- Possible transparent target (cryo frozen argon), with dopant layer to light up as shock wave passes through.

# Diagnostic and target station development

- New target chamber with enhanced capability for diagnostics to be designed for installation on NDCX-II.
- Diagnostic upgrades to accommodate higher temperature, smaller spot size in NDCX-II
- Cryo-target capability
- X-ray diagnostics
- Thomson scattering
- Beam and accelerator diagnostics
- Laser-based diagnostics
- High-power pulsed laser systems, e.g. driving shocks

# Summary

- NDCX-I provides a test bed for target physics studies, target diagnostics development, and ion beam compression studies.
- Experimental and diagnostic capability have been developed in experiments studying target evolution and droplet formation. These will be readily transferred to NDCX-II, which will have much greater capability than NDCX-I.
- Future experiments with NDCX-I and NDCX-II will explore aspects of WDM physics including beam manipulation, high electron affinity targets, beam-target coupling, etc.
- We encourage participation in the experiments to increase productivity of the facility, including development of new diagnostics.